Executive Summary

Challenges in the 21st Century

The international community today faces many energy-related issues, including a predicted worldwide depletion of petroleum resources, the need of every nation to have secure energy supplies, and the potential for global climate changes. Other major challenges (such as smog and air pollution) occur most often on local and regional scales; therefore, nations must address those issues individually or in partnership with neighboring countries. It is well-known that motor vehicles contribute significantly to all of these issues (even as they offer us many benefits), so it is vital that we find ways to reduce or remove their impact on our energy resources and environment.

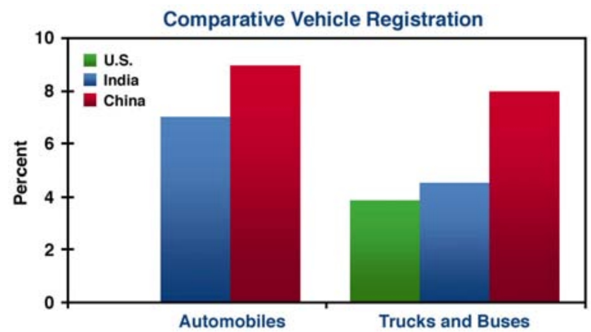

Figure ES1. Comparative vehicle registration percentage change from 1991 to 2001.

Our nation's energy security depends significantly on the efficiency of our transportation system and on which fuels we use. Transportation in the United States already consumes much more oil than we produce here at home–and the situation is getting worse. Domestic oil production has been dropping steadily for over 20 years, and by 2025 it is predicted that about 70% of our oil will be imported. Importing oil will remain a problem, because our petroleum resources are far away and found mostly in politically or environmentally sensitive areas. Another cloud on the horizon is the rapidly escalating worldwide demand for oil, especially in countries such as China and India, where the number of motor vehicles in use is growing much more quickly than here in the United States.

Our nation's energy security depends primarily on the efficiency of our transportation system and on what fuels we use. So it is vital that we find ways to reduce or remove the impact of motor vehicles on our energy resources and environment.

Responding to the Challenges

The U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies (FCVT) Program manages research and development (R&D) sub-programs to help make cars and trucks more energy-efficient, while at the same time developing technologies that will help transition the United States to using vehicles that do not require petroleum fuels. FCVT's R&D will provide benefits over the next two or three decades as more and more energy-efficient vehicle technologies become available to car buyers. The FCVT

The next 30 years may see even more dramatic innovations in vehicles: more hybrid vehicles on the road; increased use of lightweight materials; higher-efficiency engines; the use of alternative fuels, such as hydrogen, in conventional engines; and hydrogen-powered hybrid fuel cell vehicles.

program is also making a significant contribution as part of the President's Hydrogen Fuel Initiative aimed at developing cars that are "powered by hydrogen and pollution-free."

Thirty years from now, new vehicles will be as dramatically different as today's cars are from vehicles built three decades ago. Beginning in the mid-1970s, the use of front-wheel-drive powertrains and lighter materials helped reduce the mass of the average passenger car by a thousand pounds, fuel injectors replaced carburetors, and computers came to control many vehicle operations, such as engine performance, cruise control, and interior climate controls. Thirty years ago, safety features such as airbags, anti-lock brakes, and traction and stability control were rare or nonexistent. And, of course, thanks to improved engines and catalytic converters, light-duty vehicles now emit 99% less pollution than before. History also shows us that fuel economy can rapidly and significantly improve when market conditions warrant it, as in the 10 years following 1978 when domestic automakers increased the average automobile's fuel economy by nearly 50% (from 18.7 to 27.4 mpg).

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The FCVT Role

The Office of FreedomCAR and Vehicle Technologies supports R&D that will lead to new technologies that reduce our nation's dependence on imported oil, further decrease vehicle emissions, and serve as a bridge from today's conventional powertrains and fuels to tomorrow's hydrogen-powered hybrid fuel cell vehicles.

The U.S. government primarily supports "basic" R&D, because it is typically less attractive to private industry because of the higher risk of failure and the longer payback periods involved in turning the fewer successes into marketable technology. However, there are times when national needs provide a compelling case for the government to support "applied" R&D, which typically has technological payoffs that are more immediate–the need for energy security and the risk of global climate change are two good examples. This *Multi-Year Program Plan* specifically addresses the national issues of energy and the environment. The approach for government-supported automotive research has been to involve the affected industries in planning the research agenda and identifying technical goals that, if met, would provide the basis for commercial opportunities. So a concise description of the automotive research approach taken here is *"industry-wide collaboration in pre-competitive research, then competition in the marketplace."*

Partnering for Success

FCVT is collaborating with the U.S. Council for Automotive Research (USCAR) and the energy sector in the FreedomCAR and Fuel Partnership to improve vehicle efficiency in the near term and to facilitate the transition to hydrogen-powered hybrid fuel cell vehicles over the long term. In the 21st Century Truck Partnership, FCVT is teaming with three other federal agencies and 15 industry partners representing heavy-duty vehicle engine manufacturers, truck and bus manufacturers, and hybrid vehicle powertrain suppliers. Involving key industry participants greatly improves commercial opportunities for FCVT-supported technologies.

There is a track record of success with the R&D supported by FCVT and its predecessor organization, the Office of Transportation Technologies. The focus of the research has always been on pursuing technologies that were not "sure bets" for success and that might take many years to develop. This emphasis by government on "high-risk" technologies helps avoid potential conflicts with private industry, which is also trying to develop and commercialize new technologies. Thus government-supported "high-risk" research has been well-regarded and provides a substantial base for improving energy efficiency in transportation.

Since the formation in 1993 of the government-industry research alliance called the Partnership for a New Generation of Vehicles (PNGV), automotive research conducted at the DOE national laboratories has received 16 R&D 100 Awards, 3 *Discover Magazine* Awards, and 6 awards from the Federal Laboratory Consortium for Excellence in Technology Transfer. In addition, one of FCVT's researchers at a national lab was named by *Scientific American* magazine as one of its "*Scientific American* 50" top research leaders of 2003.

Other successes include computer codes developed by FCVT that are widely used by industry and academia to simulate or control the performance of everything from individual vehicle components to entire vehicle systems. FCVT also maintains specialized facilities at national laboratories for use by government, industry, and universities for fundamental research and for developing

The focus of the research has always been long-term, high-risk technologies. Government-supported "high-risk" research has been well-regarded and provides a substantial base for improving energy efficiency in transportation.

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innovative, reliable transportation technologies. These specialized facilities include the Advanced Powertrain Research Facility, the Renewable Fuels and Lubricants Laboratory, the High Temperature Materials Laboratory, and the National Transportation Research Center. FCVT and its partners also make extensive use of the Office of Basic Energy Sciences' Combustion Research Facility.

The Technical Plan

This *Multi-Year Program Plan* details the structure of FCVT, the goals of its research activities, the current status of the R&D, the technical barriers that need to be overcome, and the approach taken by FCVT to conduct the needed research. Descriptions of each of the research tasks are provided, as are the associated milestones. In addition, critical decision points are identified so that informed judgments can be made on whether a particular line of R&D should be continued as is, modified, or even discontinued.

The FCVT Program Office has worked with industry to identify seven major technology sub-programs that support research needed to develop more fuel-efficient vehicle technologies. The research performed by the sub-programs might also have application beyond use in automobiles. To clarify the relationships among the seven technology sub-programs and the performance goals established for both auto and truck applications, a matrix is provided at the end of this Executive Summary. Overviews of the seven research sub-programs are provided here, while details are provided in the following chapters.

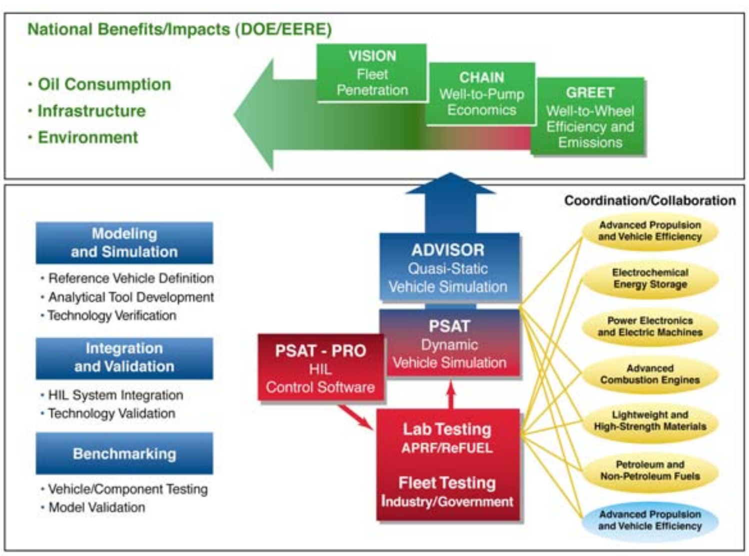

Figure ES2. Model by which the sub-programs meet the goals of the Office of FreedomCAR and Vehicle Technologies.

Vehicle Systems Analysis and Testing

This sub-program is overarching in that it focuses FCVT research at the component and subsystem levels by using modeling and simulation to test and specify component requirements in vehicle systems. "Hardware-in-the-loop" simulations allow components to be controlled and evaluated in emulated vehicle environments.

Laboratory testing is used to measure progress toward FCVT technical goals and eventually to validate the DOE-supported technologies through testing at specialized DOE facilities.

Advanced Propulsion / Vehicle Efficiency

Much of the focus in this area has been on developing hybrid technology, which has helped stimulate interest worldwide in hybridization to improve fuel economy. Now the research focus for hybrid technology is on optimizing performance, reducing costs, and minimizing the fuel economy penalty required to achieve stricter emissions control. In addition, work on advanced propulsion will address the FreedomCAR and Fuel Partnership goal of developing a cost-competitive internal combustion engine that operates using only hydrogen fuel, which serves the dual purpose of reducing vehicle emissions and facilitating a future transition to hydrogen hybrid fuel cell vehicles.

Fuel savings in heavy-duty vehicles (Class 3–8 trucks and buses) can also be enhanced by hybrid technologies, but they require modifying some components and control strategies as indicated by system-level modeling. The goal of heavy-hybrid propulsion research is a 60% improvement in fuel economy by 2012, using cost-effective components that also meet U.S. Environmental Protection Agency emissions standards.

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Improvements in vehicle efficiency can also be accomplished by (1) reducing the amount of fuel required to operate ancillary systems in light-duty vehicles (e.g., passenger cabin climate controls), (2) reducing parasitic energy losses (e.g., aerodynamic drag, friction and wear, and overnight engine idling), (3) using regenerative shock absorber devices, (4) using a diesel fuel reformer to prevent coking, and (5) improving thermal management in heavy-duty vehicle engines.

Energy Storage Technologies

Energy storage is critical for near-term hybrid vehicle improvements, as well as the long-term goal of hybrid fuel cell vehicles. There are three closely related research areas. First, full battery system development is under way with R&D on lithium-sulfur batteries for electric vehicles and lithium-ion batteries for both high power density (for hybrid

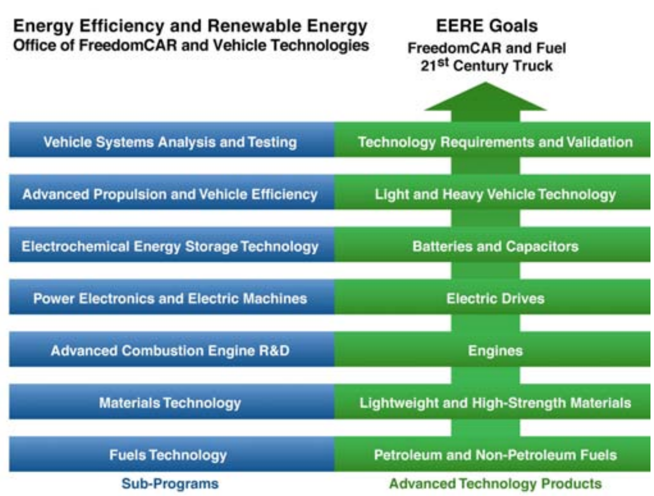

Figure ES3. FCVT R&D areas and resulting advanced technologies.

vehicles) and high energy density (for electric vehicles). Second, applied battery research is conducted on the cost, battery life, and abuse tolerance of lithium-ion cells. Third, long-term exploratory battery research is focused on the fundamental problem of chemical instabilities that impede the development of advanced batteries. A priority FCVT goal is to reduce the production cost of a high-power 25-kW battery from $3000 in 1998 to $500 in 2010, with an intermediate goal of $750 in 2006 (all values assume a production level of 100,000 batteries per year). These goals were established by a technical team representing DOE, the auto industry, and battery manufacturers and are based on the costs that will be required to ensure that this technology is competitive with a comparable internal combustion engine in the automotive marketplace.

Power Electronics / Electric Machines

Advanced power electronics (e.g., inverters, capacitors, motor-controllers, and other power management or interface devices) are key components for hybrid vehicles and, ultimately, for hybrid fuel cell vehicles. Work focuses on improving performance, developing low-cost materials, and improving thermal management systems to produce higher power output. Developing electronics for vehicle applications is particularly demanding, as they must be highly reliable under adverse conditions while also being low in cost, lightweight, and compact.

Advanced Combustion Engine R&D

In the near- and mid-term, research that dramatically improves engine combustion efficiency can significantly reduce petroleum consumption. Combustion research is "crosscutting" in that there are synergies between research on light-duty, medium-duty, and heavy-duty vehicles. Work in this area seeks to expand our fundamental knowledge of engine combustion and the technical barriers related to emissions control, engine controls (e.g., ignition timing, rate of heat release, transients, and cold starts), and costs. FCVT's research approach is designed to better understand in-cylinder combustion and emissions formation, improve the effectiveness of exhaust aftertreatment technologies, and optimize fuel formulations.

Waste heat recovery could enable developing a diesel engine with a thermal efficiency of 55%.

Longer-term goals for engine R&D include developing a cost-effective "waste heat" recovery system that overcomes barriers such as system packaging (size), scaling up of existing advanced devices (e.g., quantum well thermoelectrics), and the need to greatly improve system durability. Waste heat recovery could enable developing a diesel engine with a thermal efficiency of 55%. Other work in this area involves exploring the relationships between mobile emissions generated by using new fuels and technologies and any quantifiable health hazards. This activity is intended to preclude introducing promising new fuels or technologies that could have undesirable health effects.

Materials Technologies

To improve vehicle efficiency, high-strength, lightweight materials will be needed for the frame, body, chassis, and powertrain systems. Concept prototype vehicles already demonstrate the significant progress made in reducing vehicle mass, but the materials and manufacturing costs remain relatively high. FCVT technical targets focus on making these materials more affordable while also meeting vehicle performance, safety, and recyclability objectives. Materials of interest include carbon fiber, titanium alloys, magnesium alloys, metal matrix composites, and thermoplastic resin systems. Based on the material, issues also being addressed include primary metal production, advanced reinforcement, joining, designing, and glazing.

Automotive Propulsion Materials research focuses on improving engine efficiency and reducing component costs for power electronics. Carbon foam is being investigated for use in keeping power electronics cool, and long-life filters are being developed to trap diesel particulates.

Reducing parasitic energy losses in heavy-duty vehicles is the goal of FCVT's High Strength Weight Reduction Materials work. Specific goals include reducing the weight of an unloaded tractor-trailer vehicle by 5000 pounds (22%) and reducing the weight of other classes of heavy vehicles by 10 to 33%, depending on performance requirements and duty cycles.

Heavy Vehicle Propulsion Materials research aims at developing entirely new or improved materials for heavy-duty engines that meet the high durability and reliability requirements of these vehicles. This type of work includes developing materials that reduce erosion and corrosion in heavy-duty engines caused by exhaust gas recirculation and developing materials that help engines achieve efficiencies of over 50% while meeting future emissions standards.

The High Temperature Materials Laboratory is another part of this sub-program. As a user facility, it provides

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The goals are to identify fuel specifications that in the near term can replace 5% of petroleum fuels, and in the mid-term can be used in advanced combustion systems to sustain petroleum displacment by 5%.

government, industry, and universities with state-of-the-art materials characterization for fundamental research.

Fuels Technologies

The Advanced Petroleum-Based Fuels (APBF) and Non-Petroleum-Based Fuels (NPBF) activities are undertaken to (1) enable current and emerging advanced combustion engines and emission control systems to be as efficient as possible while meeting future emission standards, and (2) reduce reliance on petroleum-based fuels. Fuels R&D is a critical enabling element in the development of near-term and long-term technologies being championed by the Advanced Combustion Engine R&D subprogram. Even near-term engine technologies (i.e., prototypes of technologies being evaluated by industry for sale in model year 2007) have shown emissions and performance impacts from variations in fuel properties. Because of such sensitivity, fuel property requirements and engines must be *co-developed*. Co-development of in-cylinder combustion technology and fuels will allow FCVT to fully exploit the potential of high-efficiency advanced-combustion-regime technology. In addition to enabling advanced engine technologies, NPBF has the potential to allow *direct displacement* of a portion of the petroleum used for transportation. The goals of the Fuels Technologies subprogram are to develop technologies and fuel specifications with the potential to allow displacement of 5% of petroleum from near-term technology (i.e., direct-injection diesel) and to sustain that 5% displacement in the transition to mid-term to long-term advanced combustion technology (e.g., homogeneous-charge compression-ignition engines). The New Technologies Impacts activity, also within the subprogram, is intended to evaluate the potential adverse effects on the environment of all fuel formulation modifications as the data are being developed. This activity will provide FCVT the opportunity to avoid problems created in the past by the inclusion of such materials as tetraethyl lead and MTBE in fuels.

Vision for the Future

Success in developing and marketing advanced energy-efficient technologies in our nation's vehicles will provide significant benefits.

- **Increased Energy Security**: By 2040, FCVT Program technologies should save about 4 to 6 million barrels of oil per day, depending on the timing and success of hybrid fuel cell vehicles. Oil savings due to FCVT technologies will continue to grow should there be any delay in hybrid fuel cell vehicle commercialization.

- **Improved Environment**: Hybrid, light-duty vehicles can help reduce greenhouse gas emissions by 50% on a total energy cycle basis. Fuel economy improvements achieved by heavy-duty vehicles will contribute to a reduction in greenhouse gas emissions, as carbon emissions are directly related to petroleum fuel use.
- **Economic Competitiveness**: One of the direct benefits of FCVT's R&D is that U.S manufacturers can be more competitive against countries that pay workers lower wages in the globally competitive automotive and truck markets. In addition, reducing petroleum use lessens the potential for future oil price shocks and the resulting economic consequences.

Meeting the goals for both the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership will provide a pathway for the United States to dramatically reduce its energy use and petroleum dependence and significantly decrease emissions and transportation-generated greenhouse gases, while sustaining mobility and freedom of choice for car buyers. This vision can benefit everyone throughout the United States.

The benefits will include saving 4 to 6 million barrels of oil per day, reducing greenhouse gas emissions by 50%, and enabling U.S. manufacturers to be competitive in the global market.

Office of FreedomCAR and Vehicle Technologies Technologies/Goals Matrix

Each of FCVT's seven sub-programs has research activities that are directly related to one or more of the goals of the FreedomCAR and Fuel Partnership or 21st Century Truck Partnership. The following matrix shows the relationships.

Technology is a major contributor to achieving this goal ●

Technology contributes to achieving this goal ○

Technology is not a contributor to achieving this goal

Goals	Vehicle Systems Analysis and Testing	Advanced Propulsion and Efficiency	Energy Storage Technologies	Power Electronics and Electric Machines	Advanced Combustion Engine R&D	Materials Technologies	Fuels Technologies
Electric Propulsion Systems							
Achieve 15-year life and capability to deliver at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kW peak	○	○	○	●		○	
Internal Combustion Engines							
Improve the efficiency of internal combustion engines from 30% (2002 baseline) to 43% by 2010	○	○		○	●	○	○
Electric Energy Storage							
Reduce the production cost of a high-power 25-kW battery for use in light vehicles from $3000 in 1998 to $500 in 2010	○		●	○		○	
Materials and Manufacturing							
Reduce the weight of vehicle structure and subsystems by 50%, increase affordability, and increase use of recyclable/renewable materials	○				○	●	
Reduce the weight of a tractor-trailer from 23,000 lb in 2003 to 18,000 lb in 2010 (a 22% reduction),	○					●	
Hydrogen Internal Combustion Engine							
Achieve engine cost of $45/kW by 2010 and $30/kW in 2015, peak efficiency of 45%, and capability to meet or exceed emissions standards (shared responsibility)	○	●		○	●	○	
Engine Systems							
Increase the thermal efficiency of heavy truck engines to 55% while reducing emissions to near-zero levels.	○	●		○	●	○	○
Develop diesel fuel that uses renewables and other non-petroleum agents and achieves high efficiency and low emissions while displacing petroleum fuels by 5% by 2010	○	○			○		●
Heavy Duty Hybrids							
Develop a drive unit that has 15 years of characteristic life and costs no more than $50/kW peak electric power rating	○	●	○	○		○	
Develop heavy hybrid propulsion technology that achieves a 60% improvement in fuel economy, on a representative urban driving cycle, while meeting regulated emissions levels for 2007 and thereafter	○	●	○	○	●	○	○
Develop an energy storage system with 15 years of characteristic life that costs no more than $25/kW peak electric power rating	○	○	●	○		○	
Parasitic Losses							
Reduce heavy truck parasitic losses (e.g., aerodynamics, ancillary systems) from 39% of engine output in 1998 to 24% in 2006	●		○	○		○	
Reduce the aerodynamic drag of a Class 8 highway tractor-trailer combination by 20% (from a current average drag coefficient of 0.625 to 0.5)	●					○	
Reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers	●			○		○	